

Analysis of the breakdown in single-chamber circuit breaker

Karim BOUSOLTANE, Guilherme LINHARES, Pierre CHEVRIER & Georges GAUDART

Siemens H2 Grenoble Factory
Rue de la Neva 38000 Grenoble
karim.bousoltane@siemens.com

Abstract :

A hydrodynamic model for electrical arc modelling was used to develop a 420 kV 50 kA single-chamber circuit breaker. Normally, in order to estimate the gas breakdown probabilities, calculations based on gas density and the electric field are used. A second approach involves the use of energy equations to determine the re-strike possibility through the creation of a leader channel. Leader parameters and more accurate predictions are obtained by comparing the experimental results and the leader calculations. However, these criteria assume a re-strike in pure gas, which is not true after introduction of the self blast volume.

Résumé :

Un modèle hydrodynamique prenant en compte l'arc électrique a été développé afin de dimensionner un disjoncteur 420kV 50 kA mono chambre. Pour estimer les probabilités de reclaquage dans les gaz on couple un calcul de densité d'une part et un calcul de champs électrique d'autre part. Mais une nouvelle approche a été développée, une approche énergétique, qui permet de déterminer la possibilité de création d'un canal leader. Ces deux critères supposent que l'on ne reclaque que dans du gaz pur, ce qui n'est plus le cas depuis l'introduction de l'auto-expansion.

Key-words :

Breakdown ; Leader ; Switchgear

1 Introduction

A 420 kV 50 kA single-chamber circuit breaker (CB) has been designed using software which takes into account the interaction between compressible flows and the electric arc. The calculations are used to identify the best design of the active parts of the chamber (contacts, nozzle, inner nozzle, thermal volume shape) according to the most critical performances requirements of the circuit breaker.

In the proposed hydrodynamic model, the electric arc and the ambient gas flows are considered as the same compressible fluid. The electric arc is defined as the conducting part of the hot fluid. The software used in our analysis takes into account the interaction between the electric arc and the insulating parts (PTFE), and has been validated by comparisons between calculations and measurements Chevrier *et al.* (1997).

The purpose of the paper is to present and discuss the criteria used to analyse the calculation results of the post-recovery period of short-circuit tests. These criteria take into account the electric field, the temperature, the gas density and the pressure of the gas between the contacts after current 0.

2 Hydrodynamic model for arc modelling

The main characteristics of the flows in CB are :

- **Compressible flows** with shock waves
- **Transient flows** : There is a lot of transient physical phenomena, due to the very short time characteristic. This time represent one period of 50 Hz alternative current (20ms), which makes the turbulence negligible.
- **Electric arc** : The boundaries of the electric arc behave in the same way of a "contact discontinuity" with a very hot gaz (30000K) which conducts the current next to a colder gas (3500K) which is an isolent.

The model uses the compressible 2D Navier Stokes (NS) equations with the assumption of Local Thermodynamic Equilibrium (single temperature for all the species), with an additional equation to estimate the proportion of the gases (SF_6 , PTFE vapours). As our applications have azimuthal symmetry, we used a 2D axi symmetrical formulation. The model could then be written as follows:

$$\frac{\partial \rho_{mixture}}{\partial t} + \frac{\partial(\rho_{mixture}.v_z)}{\partial z} + \frac{\partial(\rho_{mixture}.v_r)}{\partial r} = 0 \quad (1)$$

$$\frac{\partial(Y.\rho_{mixture})}{\partial t} + \frac{\partial(Y.\rho_{mixture}.v_z)}{\partial z} + \frac{\partial(Y.\rho_{mixture}.v_r)}{\partial r} = 0 \quad (2)$$

$$\frac{\partial(\rho.v_z)}{\partial t} + \frac{\partial(\rho.v_z^2 + P)}{\partial z} + \frac{\partial(\rho.v_z.v_r)}{\partial r} = f_z \quad (3)$$

$$\frac{\partial(\rho.v_r)}{\partial t} + \frac{\partial(\rho.v_r^2 + P)}{\partial r} + \frac{\partial(\rho.v_z.v_r)}{\partial z} = f_r \quad (4)$$

$$\frac{\partial \hat{E}}{\partial t} + \frac{\partial[(\hat{E} + P).v_z]}{\partial z} + \frac{\partial[(\hat{E} + P).v_r]}{\partial r} + divQ = S \quad (5)$$

with the following notations: t is the time (s), $\rho_{mixture}$ is the mixture density (kg/m^3), Y the massic proportion, $V = (v_r, v_z)^t$ is the velocity (m/s), $\hat{E} = \rho(V^2/2 + e)$ is the total energy (J/Kg), e is the specific internal energy (J/Kg), $S = \Sigma - R$ is the joule heating term ($W.m^{-3}$) minus the radiation term ($W.m^{-3}$), $Q = -k(T) grad(T)^t$ is the heat-flux vector ($W.m^{-2}$), $k(T)$ is the thermal conductivity ($W.m^{-1}.K^{-1}$), T is the Temperature (K), $P = f(T, \rho)$ is the pressure (Pa) and $F = (f_r, f_z)$, is the Lorentz force ($kgm^{-2}s^{-2}$).

In CB, and during the interruption phase, the filling gas temperature can reach 30000K; in that situation it's necessary to take into account the dissociation and the ionisation of the gas. These aspects are taken into account through the real state equation as Chevrier *et al.* (1997) and Chevrier *et al.* (1999). Our software considerate only the energetic effect of the current. The electric arc is assumed as gas with a higher conductivity, what allows to introduce the joule effect and the radiations as a source term in the energetic equation of the NS system. For high voltage the nozzle (PTFE) ablation phenomenon have a non-negligible effect on the flows, and are taken into account in this modelling. This part is based on the energy conservation at the boundary condition between the flow and the wall (PTFE).

3 High voltage Interrupter

The analysis is based on a SF_6 self-blast high voltage circuit breaker currently under development. This circuit breaker has a spring-operated mechanism. The chamber includes two different volumes (see Figure 1): the puffer volume and the self-blast volume. The small currents are broken by puffer effect and the extinction of the highest currents is obtained through

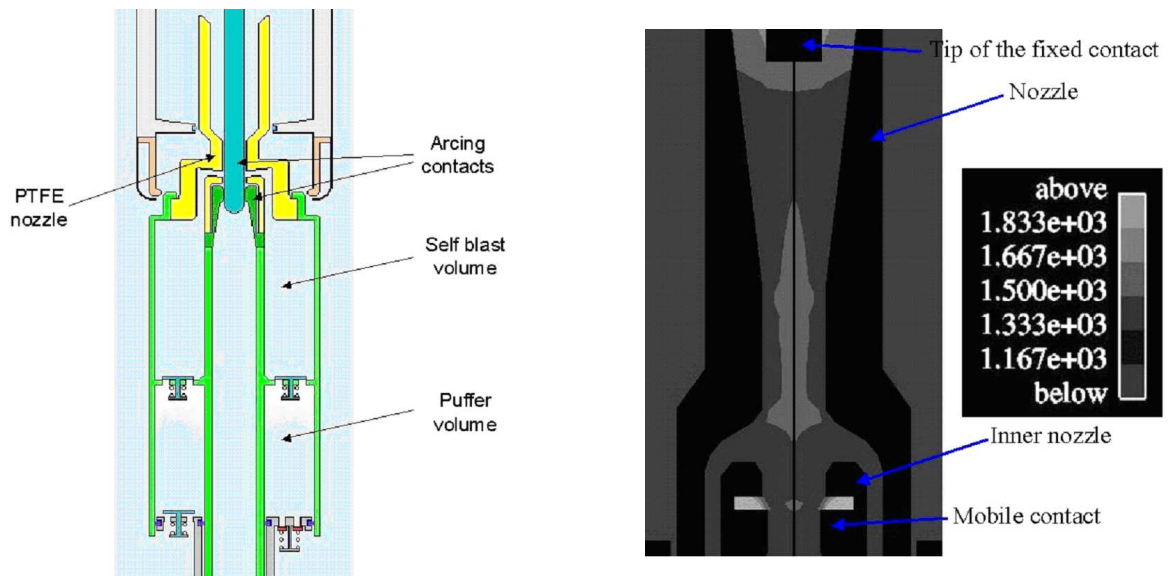


Figure 1: Self blast chamber (write) Gas temperature between the electric contacts at TRV peak instant (left)

the self-blast effect of the electric arc itself. The PTFE nozzle aids extinction, firstly, by the increase of pressure due to its sublimation, and secondly by driving the flows.

Every circuit breaker have to pass a series of tests (CEI -62271-100) : they have to break the current and not to re-strike when faced with the Transient Recovery Voltage (TRV).

4 Calculation results, $\frac{E}{\rho}$ criteria

4.1 Temperature, density maps

The temperature and density maps at TRV peak instant are given below.

The temperature (Figure 1) between the 2 arcing contacts is around 1500K, which means that SF_6 is steel dissociated. The density (Figure 2) between the 2 arcing contacts changes dramatically at the nozzle throat. At the tip of the fixed contact (high electric field region), it is around $10kg/m^3$ whereas it is lower than $5kg/m^3$ at the nozzle throat.

4.2 Density and Electrical field coupling

For gas temperature below 1000 K, breakdown voltage is proportional to gas density. Above this temperature, Shinkai *et al.* (2000) calculated $(\frac{E}{N})_{crit}$ of SF_6 gas under a uniform electric field as a function of the temperature, where $(\frac{E}{N})_{crit}$ is the critical value of the breakdown electric field divided by gas number density.

The flow and dielectric calculations allows us to locally calculate the dielectric ratio $\frac{E}{\rho}$ at the TRV peak.

Focussing our analysis in the fixed contact region, we can present the profiles of both electric field (E) and dielectric ratio $\frac{E}{\rho}$ from the tip of the contact up to 20mm from it (Figure 3).

Instead of the decrease of the electric field from the tip of the fixed contact, the maximal value of the dielectric ratio $\frac{E}{\rho}$ is reached at 16mm from the contact tip, due to the low densities after the nozzle throat. Knowing the local temperature (around 1500K) and using the dielectric strength in SF_6 as a function of the temperature Shinkai *et al.* (2000), it is possible to determine if the flow conditions are sufficiently efficient to avoid any dielectric breakdown. The dielectric

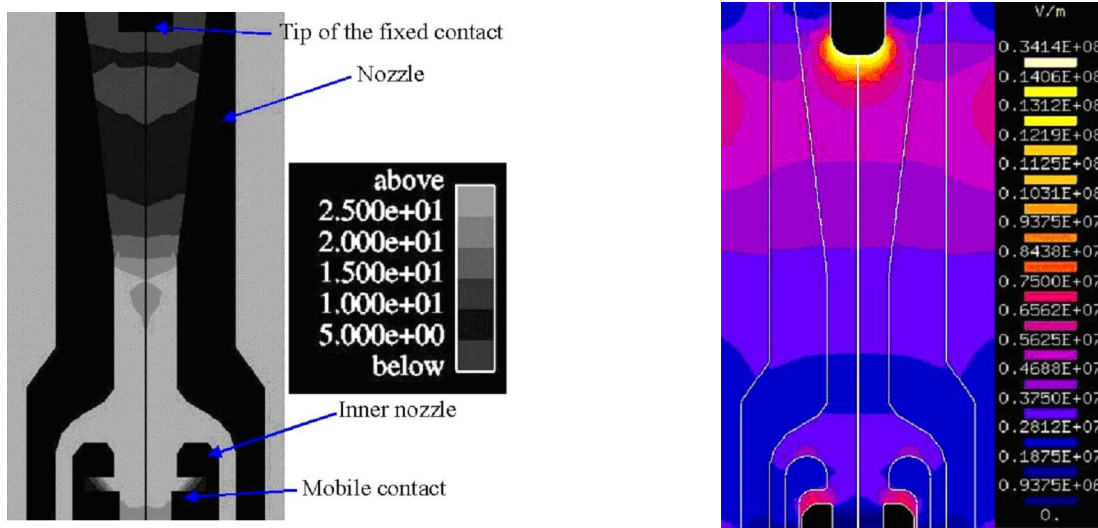


Figure 2: Gas density (right) Electric field (left) between the electric contacts at TRV peak instant

strength of SF₆ in an homogeneous electric field at 1500K is $1.2 (kV/mm)/(kg/m^3)$.

5 Leader calculations

In this paragraph, an energetic approach of the dielectric breakdown due to a leader creation is proposed.

5.1 Leader Formation Energies

As suggested by Boggs, it is possible to compare the available and the requested energy to form a leader:

- **The available energy** to form a leader derives from the background electric field. The local electric field under TRV peak has been calculated and the available energy has been interpolated using the results presented in Boggs *et al.* (2003).
- **The requested energy** is that required to increase the temperature of the leader channel from the local temperature (around 1500K in our case) up to 3500K. 3500K is taken as the reference temperature for SF₆. At this temperature the gas is fully dissociated and can be considered as conducting. The requested energy is calculated by integrating the local gas energy density from the local calculated temperature up to 3500K (see equation 6). Gas density is assumed to remain constant during the integration process.

$$E_{req} = \int_{leadervol} \int_{T_0}^{3500} \rho \cdot C_v \cdot dt \cdot dv \quad (6)$$

As in Shinkai *et al.* (2000), the channel is assumed to be a long, thin spheroid of length L and radius r . The volume of the leader is:

$$Vol = \frac{2}{3} \cdot \pi \cdot L \cdot r^2 \quad (7)$$

If the available energy is greater than the requested one, then it is reasonable to suggest that a dielectric failure could occur. In the opposite case, if the requested energy is greater than the

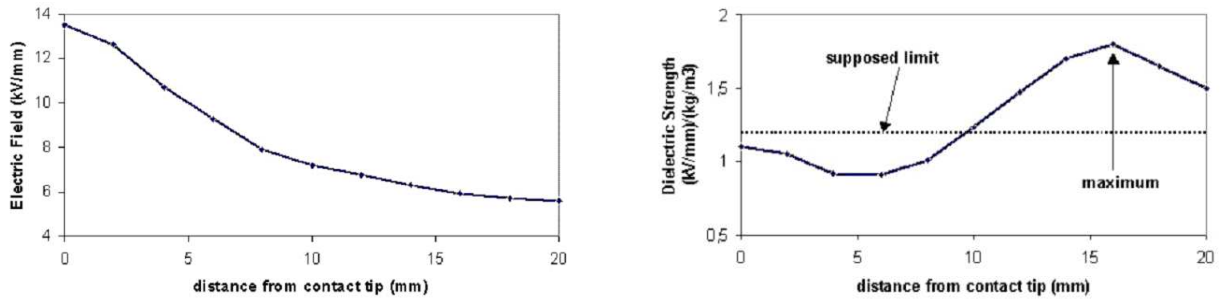


Figure 3: E profile(left) E/ρ profile(right) at the top of the fixed contact (from the tip of the contact up to 20mm from it)

available energy then it is reasonable to think that the interruption performance is sufficient to avoid any dielectric failure.

5.2 Most probable leader parameters

In these energy calculations the 2 key parameters are the length and the radius of the channel. An important issue is to have experimental re-strikes (available energy equals required energy) to calculate the most probable parameter of a leader.

These calculations assume that the leader is located at the tip of the fixed contact with a leader radius of $2\mu m$. The local gas state variables (temperature, density and pressure) are taken from the flow calculations at the re-strike instant. This method was applied for a large number of experimental failures. This calculations suggest that the most probable parameters for a leader are:

- Length: 10mm
- Radius: $2\mu m$

5.3 Interpretation of flow simulations taking into account leader parameters

The leader energy calculation are compared to the experimental results; of course the available energy is higher than the requested energy for re-strike cases. The leader parameters revealed suggest that a local analysis of the critical results (T , ρ , $\frac{E}{\rho}$) is not a good way to define the breakdown probabilities. For instance, it is not relevant to fix a maximum value for $\frac{E}{\rho}$ criteria as a function of the temperature. Indeed, it is necessary to look for $\frac{E}{\rho}$ average value on a length compatible with a possible leader. On that way, it is possible to understand why no breakdown was observed even if the supposed $\frac{E}{\rho}$ limit was overcome locally.

6 Discussions: The effect of PTFE vapors on breakdown parameters

These criteria ($\frac{E}{\rho}$, leader) are based on one hypothesis: The breakdown will occur in pure SF_6 . This hypothesis was valid when the switchgear was based on the puffer technology, but now the CB geometries are more and more complicated and specially when the self-blast volume had been introduced (Figure 2).

In the high voltage applications the flow and the electric arc are guided by a Teflon nozzle. The high temperature of the gas and the radiation induces nozzle sublimation.

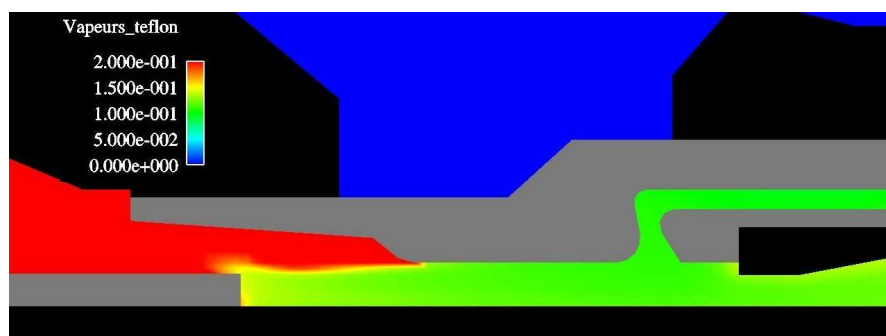


Figure 4: Distribution of teflon vapours after the current zero

In modern CB these vapours are used to increase the pressure in the self-blast volume during the high current period. Then, in the zero current phase, these vapours are found in the high electric field area. Then the dielectric strength is not the dielectric strength of the pure SF_6 but that of the SF_6 and PTFE mixture (Figure 4) and the mixture proportion will change with the geometry, the PTFE composition, and the current.

7 Conclusions

Combining experimental results and flow calculations in the interruption chamber, allows us to determine the most probable leader parameters in case of breakdown at TRV peak. The parameters revealed (Length=10mm, Radius= $2\mu m$) are in very good agreement with those proposed in a completely different configuration Ushii *et al.* (2004). They suggest that the calculations should not be interpreted according just to the local results (especially E or $\frac{E}{\rho}$ criteria), but to integrate them on volume compatible with a 10mm length leader. Until now, the vapours having a non-negligible influence on the dielectric strength have not been taken into account.

References

- P. Chévrier, M. Barrault, C. Fiévet, J. Maftoul, J. Millon-Frémillon 1997 Industrial Applications of High-, Medium- and Low-Voltage Arc Modeling *J. Phys. D: Applied Phys* pp. 1346-1355.
- P. Chévrier, P. Scarpa, C. Fleurier, F. Gentils, M. Barrault, C. Fiévet 1999 Arc Nozzle Interaction in SF_6 Circuit Breakers: Experiments and Modeling *ICIPIG*
- T Shinkai, T Mori, G.J. Cliteur, K. Suzuki, D Biswas. 2000 Uniform dielectric breakdown in hot SF_6 Application to Gas Circuit Breakers *T IEE Japan* vol.120-B, N°1, 2000.
- S. Boggs, T. Uchii, S. Nishiwaki July 2003 Analytical Approach to SF_6 Breakdown Under Transient Conditions *IEEE Transactions on Power Delivery* pp. 751-757, Vol. 18, No3
- T. Uchii, S. Nishiwaki, S. Boggs January 2004 Effects of Hot SF_6 on Post-Arc Circuit Breaker Design *IEEE Transactions on Power Delivery* pp. 124-130, Vol. 19, No1